

Biomass accumulation and nutrient uptake of 16 riparian woody plant species in Northeast China

Shuai Yu • Wei Chen • Xingyuan He • Zhouli Liu • Yanqing Huang

Received: 2014-01-05;

Accepted: 2014-04-15

© Northeast Forestry University and Springer-Verlag Berlin Heidelberg 2014

Abstract : Our research focused on eutrophication control and species screening for riparian zone vegetation restoration in the upstream reach of the Hun River. We studied 16 hardwood plant species to investigate nutrient concentrations and nitrogen and phosphorus accumulations. After about 120 days of growth in pots, these 16 species varied in dry matter biomass, ranging from 15.13 to 637.16 g. Total nitrogen (TN) and total phosphorus (TP) concentrations and distribution in roots, stems and foliage differed both within and between tested species. Mean TN and TP accumulation ranged from 0.167 to 14.730 g per plant and from 0.016 to 1.20 g, respectively. All 16 species, but especially *Lespedeza bicolor*, *Robinia pseudoacacia* and *Sorbaria sorbifolia* had strong potential to remove TN and TP from soil and could be widely utilized for the restoration of destroyed riparian zones in northeast China.


Keywords: Nitrogen, phosphorous, ecological restoration, foliage

Introduction

Eutrophication is a widespread and increasing problem in water resources in many countries (Bennett et al. 2001). Agricultural non-point source pollution remains the greatest global contributor to eutrophication (Corwin et al. 1997; Dabrowski et al. 2002).

Project funding: This work was funded by the major National Science and Technology project “Water Pollution Control and Management” (2012ZX07202008) of China and the National Science and Technology Pillar Program (2012BAC05B05).

The online version is available at <http://www.springerlink.com>

Shuai Yu ^{1,2}, Wei Chen ¹, Xingyuan He ¹, Zhouli Liu¹
Yanqing Huang¹

¹ State Key Laboratory of Forest and Soil Ecology, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, People's Republic of China; ² University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China.

E-mail: hexy@iae.ac.cn; oncehere88@gmail.com

Corresponding editor: Zhu Hong

The riparian zone receives and retains large amounts of nutrient inputs from farmland. These inputs can indirectly lead to eutrophication of rivers (Giese et al. 2003; McClain et al. 2003). Riparian zone vegetation, through interception and storage, plays an important role in protecting the river water from eutrophication (Lowrance et al. 1997; Hazlett et al. 2008; McBroom et al. 2008). Nitrogen concentration in runoff water can be reduced by 65%–100% after passing through a riparian zone forest (Spoelstra et al. 2010). Depending on the plant species, plant nutrient uptake has been shown to account for 3%–47% of nitrogen removal and 3%–60% of phosphorus removal from runoff water in the riparian zone (Cooke 1992; Tanner 1996; Kuusemets et al. 2001). The riparian zone forms an appropriate environment for nutrient removal (Lowrance et al. 1984; Lee et al. 2009). Previous studies have examined more than 50 aquatic plants (Borin and Salvato 2012) and herbs (Mcjannet et al. 1995; Yu et al. 2014). On an annual basis, forested riparian buffer strips have proven more effective at reducing nitrogen concentrations in streams than herbaceous buffers (Lowrance et al. 1984; Osborne and Kovacic 1993; Hefting et al. 2005). Poplar forest in the riparian zone proved more effective (99% retention of NO_3^-) than grass (84% retention of NO_3^-) during winter months (Haycock and Pinay 1993).

Selecting suitable woody plants for restoration of polluted, damaged riparian zones is an effective and efficient measure for controlling non-point-source agricultural inputs of nutrients (Bedford et al. 1999). However, few studies directly compared the effect of various plant species under similar conditions for extended periods of time to identify those which most efficiently accumulate nitrogen and phosphorus. This is especially true in cold temperate regions.

To fill the above information gap, we studied 16 native woody plants of 9 families to assess their performance in removing nitrogen and phosphorus from runoff water. We quantified Total nitrogen and total phosphorus concentrations, and biomass accumulations of the plants in different tissues. This research was undertaken to aid in predicting the response of species to eutrophication and providing statistical support for plant species screening for the restoration of eutrophicated riparian zones.

Materials and methods

Plant culture

Based on species lists for riparian zone forests along the Hun River, we selected sixteen woody plant species of northeastern China for study: *Syringa reticulata*, *Prunus padus*, *Robinia pseudoacacia*, *Pterocarya stenoptera*, *Juglans mandshurica*, *Berberis dielsiana*, *Sambucus williamsii*, *Salix matsudana*, *Quercus mongolica*, *Rosa davurica*, *Euonymus alatus*, *Acer truncatum*, *Populus alba*, *Lespedeza bicolor*, *Ulmus pumila*, and *Sorbaria sorbifolia*. The uniform plants (three-year-old seedlings) used in this study were bought from a nursery and cultivated in pots (five pots per species) with 8-kg un-contaminated soil (Meadow burozem soil, 6.82 pH, 2.53% organic carbon, 4.35% organic matter, 1.88 mg·g⁻¹ total nitrogen, 0.24 mg·g⁻¹ total phosphorus. After one month of growth in pots, a screening experiment was conducted from May to October 2012 at Shenyang Arboretums of Chinese Academy of Sciences (41°54' N, 123°35' E). Plants were grown under nutrient controlled conditions with nutrient solution added.

Nutrient solution was used to simulate the high nutrient input levels which typically occurred in agriculture runoff. The standard solution contained 56 mg·L⁻¹ of nitrogen (as NH₄NO₃) and 62 mg·L⁻¹ of phosphorus (as NaH₂PO₄·2H₂O), a control group was set up (CK: 0 mg·L⁻¹ of nitrogen and 0 mg·L⁻¹ of phosphorus). The nutrient addition was applied once a week. The experiment was replicated three times.

Nutrient analysis

At the end of the growing season (October), the plant samples were harvested, washed and separated into roots, stem and foliage, heated in an oven at 90°C for 30 min and dried at 65°C to constant weight. Oven-dried materials were milled and passed through a 100-mesh (0.149 mm) nylon sieve (Huafeng, Zhejiang, China), and then stored in jars prior to laboratory analyses (Lu 1999).

Subsamples were digested for total nitrogen (TN) and total phosphorus (TP) measurement according to the sulfuric acid–hydrogen peroxide (H₂SO₄–H₂O₂) method (Son and Gower 1992). TN was quantified using the semi-micro Macro Kjeldahl method (Ruizheng Kjeldahl nitrogen analyzer KDY-600D, Shanghai, China). TP was quantified using the molybdenum antimony-ascorbic acid colorimetric method (MADAC) (SHI-MADZU UV-1800 spectrophotometer, Japan).

Statistical analyses

Average values and standard errors (S.E.) were calculated by Microsoft Office Excel 2007 for all data. Statistical procedures used in this study were performed using SPSS (Version 16.0, SPSS Inc. 2007). Standard one-way analyses of variance (ANOVA) were used to test significance of differences among

and between the sixteen tested species and between roots, stems and foliage, with respect to TN, TP and biomass. Duncan multiple range test was employed to show the variation in TN and TP between species. Spearman's correlation analysis was used to determine the correlations between tissues and nutrition. Significant and extremely significant differences were set as $p < 0.05$ and $p < 0.01$, respectively. Hierarchical cluster analysis was used to classify plants into different groups based on the nutrient distribution in tissues. Origin 8.0 was used to draw figures.

Results

Total biomass

At the end of the research, the total biomass per plant was compared between the 16 tested species (Fig. 1). After about 120 days of growth, total biomass/plant differed significantly by species and treatment ($p < 0.05$, $n=3$, Fig. 1). The biomass of CK ranged from 4.20 to 237.89 g in the order: *Quercus mongolica* < *Ulmus pumila* < *Pterocarya stenoptera* < *Sambucus williamsii* < *Euonymus alatus* < *Berberis dielsiana* < *Prunus padus* < *Rosa davurica* < *Acer truncatum* < *Juglans mandshurica* < *Syringa reticulata* < *Salix matsudana* < *Populus alba* < *Sorbaria sorbifolia* < *Robinia pseudoacacia* < *Lespedeza bicolor*. The T1 (treatment) biomass per plant value ranged from 15.13 to 637.16 g in the following order: *Pterocarya stenoptera* < *Quercus mongolica* < *Ulmus pumila* < *Berberis dielsiana* < *Sambucus williamsii* < *Prunus padus* < *Rosa davurica* < *Euonymus alatus* < *Acer truncatum* < *Juglans mandshurica* < *Syringa reticulata* < *Salix matsudana* < *Populus alba* < *Sorbaria sorbifolia* < *Lespedeza bicolor* < *Robinia pseudoacacia*. T1 treatment resulted in greater biomass than CK. *Robinia pseudoacacia* and *Lespedeza bicolor* yielded more biomass than other species.

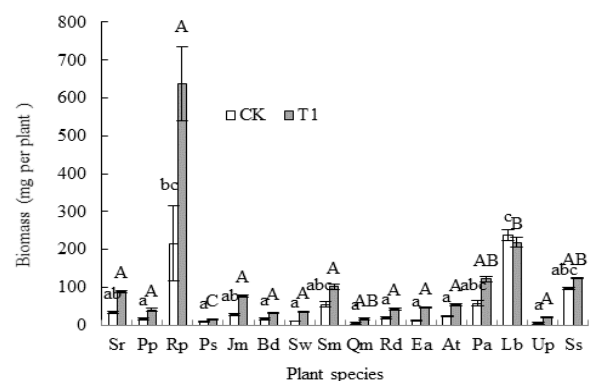


Fig. 1: The CK and T1 biomass of 16 plant species. A, B, C indicate T1 the significance different at $p < 0.05$; a, b, c indicate CK the significance different at $p < 0.05$. Error bars denote 1 SE ($n=3$). *Syringa reticulata* (Sr), *Prunus padus* (Pp), *Robinia pseudoacacia* (Rp), *Pterocarya stenoptera* (Ps), *Juglans mandshurica* (Jm), *Berberis dielsiana* (Bd), *Sambucus williamsii*, *Salix matsudana* (Sm), *Quercus mongolica* (Qm), *Rosa davurica* (Rd), *Euonymus alatus* (Ea), *Acer truncatum* (At), *Populus alba* (Pa), *Lespedeza bicolor* (Lb), *Ulmus pumila* (Up) and *Sorbaria sorbifolia* (Ss).

Variation in TN and TP concentration among tissues

For all tested species, TN and TP concentrations varied between roots, stem and foliage (Fig. 2). TN ($p < 0.05$) and TP ($p < 0.05$) concentrations in foliage were significantly greater than in roots and stems. There was no consistent pattern in the distribution of N or P concentrations in stems and roots. The plant tissues in T1 treatment had higher N and P concentrations than that did CK. The foliage of *Sambucus williamsii* and *Berberis dielsiana* had the highest TN ($35.56 \text{ mg}\cdot\text{g}^{-1}$) and TP ($5.49 \text{ mg}\cdot\text{g}^{-1}$) concentrations. The average TN concentration in roots, stems and foliage was $12.11 \text{ mg}\cdot\text{g}^{-1}$, $12.96 \text{ mg}\cdot\text{g}^{-1}$ and $22.46 \text{ mg}\cdot\text{g}^{-1}$; The TP concentration in roots, stems and foliage was $1.58 \text{ mg}\cdot\text{g}^{-1}$, $1.51 \text{ mg}\cdot\text{g}^{-1}$ and $2.51 \text{ mg}\cdot\text{g}^{-1}$, respectively.

Accumulation of TN and TP in plants

According to the analysis of TN and TP accumulations in the plants, there were significant differences in the roots, stem, foliage and among species. As shown in Tables 1 and 2, mean TN accumulated in the whole plant ranged from 166.65 to 14729.73 mg (*Quercus mongolica* < *Pterocarya stenoptera* < *Ulmus pumila* < *Rosa davurica* < *Prunus padus* < *Sambucus williamsii* < *Berberis dielsiana* < *Acer truncatum* < *Euonymus alatus* < *Juglans mandshurica* < *Syringa reticulata* < *Salix matsudana* < *Populus alba* < *Sorbaria sorbifolia* < *Lespedeza bicolor* < *Robinia pseudoacacia*) and TP ranged from 16.06 to 1203.54 mg (*Quercus mongolica* < *Pterocarya stenoptera* < *Ulmus pumila* < *Euonymus alatus* < *Rosa davurica* < *Sambucus williamsii* < *Prunus padus* < *Berberis dielsiana* < *Acer truncatum* < *Salix matsudana* < *Populus alba* < *Juglans mandshurica* < *Syringa reticulata* < *Sorbaria sorbifolia* < *Lespedeza bicolor* < *Robinia pseudoacacia*). Species *Rp* showed by a wide margin the highest accumulated TN and TP.

Spearman correlation analysis indicated that TN and TP accumulations in different tissues were positively correlated (Table 3). The Correlation coefficient ranged from 0.81 to 0.96.

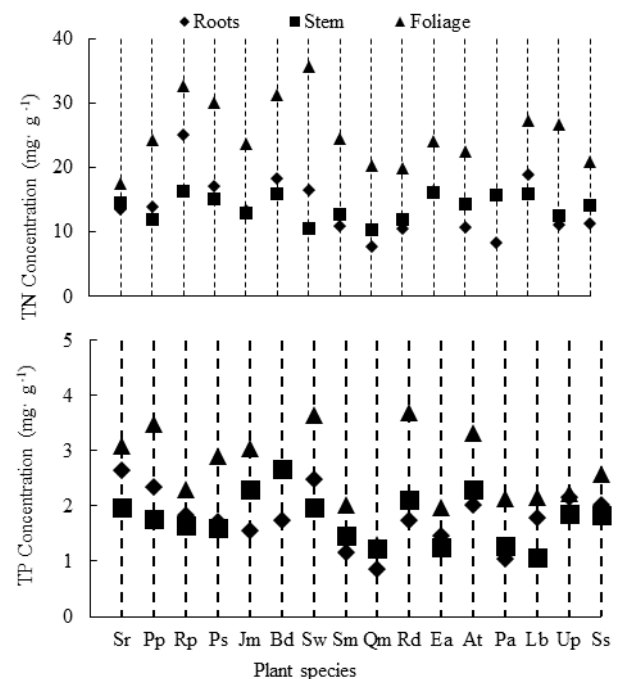


Fig. 2: Total Nitrogen and Total Phosphorus concentration (dry, wt) of plants. *Syringa reticulata* (Sr), *Prunus padus* (Pp), *Robinia pseudoacacia* (Rp), *Pterocarya stenoptera* (Ps), *Juglans mandshurica* (Jm), *Berberis dielsiana* (Bd), *Sambucus williamsii*, *Salix matsudana* (Sm), *Quercus mongolica* (Qm), *Rosa davurica* (Rd), *Euonymus alatus* (Ea), *Acer truncatum* (At), *Populus alba* (Pa), *Lespedeza bicolor* (Lb), *Ulmus pumila* (Up) and *Sorbaria sorbifolia* (Ss).

Table 1: Comparison of the TN accumulations (mg) in different tissues (roots, stem and foliage) of the sixteen tested tree species (means \pm sd)

Total Nitrogen	Roots (mg)	Stem (mg)	Foliage (mg)	Total (mg)
<i>Syringa reticulata</i>	607.67 \pm 46.65c	438.08 \pm 6.93b	230.54 \pm 3.47a	1276.29 \pm 50.12A
<i>Prunus padus</i>	227.91 \pm 20.69b	205.41 \pm 0.17ab	149.19 \pm 16.92a	582.52 \pm 37.43A
<i>Robinia pseudoacacia</i>	3898.98 \pm 546.31a	4861.19 \pm 1151a	5969.57 \pm 1169.87a	14729.73 \pm 1926.56C
<i>Pterocarya stenoptera</i>	141.77 \pm 6.18a	65.22 \pm 16.24a	74.24 \pm 28.32a	281.22 \pm 38.39A
<i>Juglans mandshurica</i>	508.55 \pm 48.41b	245.39 \pm 20.33a	461.4 \pm 45.14b	1215.34 \pm 23.59A
<i>Berberis dielsiana</i>	256.8 \pm 11.13b	179.4 \pm 18.89a	209.61 \pm 18.77ab	645.81 \pm 48.79A
<i>Sambucus williamsii</i>	293.58 \pm 4.6c	112.75 \pm 0.38a	228.16 \pm 17.8b	634.49 \pm 13.58A
<i>Salix matsudana</i>	590.11 \pm 209.36a	337.42 \pm 54.43a	418.65 \pm 182.68a	1346.19 \pm 81.11A
<i>Quercus mongolica</i>	68.13 \pm 29.46a	40.31 \pm 3.71a	58.22 \pm 3.35a	166.65 \pm 29.82A
<i>Rosa davurica</i>	238.99 \pm 14.11a	181.34 \pm 16.28a	77.14 \pm 9.21b	497.47 \pm 39.59A
<i>Euonymus alatus</i>	417.21 \pm 10.66b	202.32 \pm 5.72a	193.78 \pm 14.47a	813.31 \pm 1.91A
<i>Acer truncatum</i>	255.09 \pm 13.34a	167.04 \pm 9.83a	379.43 \pm 42.44b	801.56 \pm 65.6A
<i>Populus alba</i>	517.97 \pm 32.11b	814.6 \pm 120.35b	120.12 \pm 2.51a	1452.68 \pm 149.95A
<i>Lespedeza bicolor</i>	998.74 \pm 119.38a	1788.72 \pm 197.67b	1466.89 \pm 190.63ab	3956.23 \pm 358.43B
<i>Ulmus pumila</i>	78.68 \pm 4.14a	87.64 \pm 16.89a	176.23 \pm 25.32b	342.55 \pm 46.35A
<i>Sorbaria sorbifolia</i>	643.41 \pm 25.35b	704.77 \pm 38.06b	354.05 \pm 32.57a	1702.24 \pm 95.99A

Notes: a, b, c in the same row indicate the significance different at $p < 0.05$. A, B, C in the same line indicates the significance different at $p < 0.05$.

Table 2: Comparison of the TP accumulations (mg) in different tissues (roots, stem and foliage) of the sixteen tested tree species (means \pm sd)

Total Phosphorus	Roots (mg)	Stem (mg)	Foliage (mg)	Total (mg)
<i>Syringa reticulata</i>	120.28 \pm 9.1b	59.24 \pm 0.35a	40.77 \pm 3.14a	220.16 \pm 5.61AB
<i>Prunus padus</i>	38.34 \pm 4.44b	30.69 \pm 0.72ab	21.32 \pm 2.61a	90.2 \pm 6.33AB
<i>Robinia pseudoacacia</i>	256.99 \pm 16.08a	502.79 \pm 123.27a	441.38 \pm 102.13a	1203.54 \pm 191.09C
<i>Pterocarya stenoptera</i>	9.76 \pm 0.56a	6 \pm 1.57a	8.21 \pm 2.44a	28.26 \pm 3.45A
<i>Juglans mandshurica</i>	60.07 \pm 4.33a	43.73 \pm 2.82a	59.1 \pm 7.92a	162.94 \pm 0.77AB
<i>Berberis dielsiana</i>	24.26 \pm 1.71a	30.04 \pm 4.32a	36.73 \pm 4.75a	91.32 \pm 10.77AB
<i>Sambucus williamsii</i>	44.34 \pm 0.56b	21.17 \pm 1.09a	23.39 \pm 1.58a	88.91 \pm 0.07AB
<i>Salix matsudana</i>	41.53 \pm 0.83a	80.72 \pm 8.82b	21.55 \pm 1.33a	143.61 \pm 9.32AB
<i>Quercus mongolica</i>	7.27 \pm 2.87a	4.8 \pm 0.52a	3.73 \pm 0.2a	16.06 \pm 3.59A
<i>Rosa davurica</i>	39.69 \pm 1.54c	32.32 \pm 1.54b	14.6 \pm 0.75a	86.51 \pm 2.33AB
<i>Euonymus alatus</i>	37.4 \pm 1.06b	14.79 \pm 0.16a	17.09 \pm 0.61a	69.27 \pm 1.84A
<i>Acer truncatum</i>	48.8 \pm 2.83b	26.64 \pm 0.24a	56.56 \pm 4.31b	132.07 \pm 7.38AB
<i>Populus alba</i>	65.09 \pm 2.44a	65.76 \pm 7.9a	16.41 \pm 1.13b	147.17 \pm 6.59AB
<i>Lespedeza bicolor</i>	94.41 \pm 16.4a	119.29 \pm 21.75a	115.48 \pm 21.53a	328.39 \pm 21.13B
<i>Ulmus pumila</i>	15.36 \pm 0.04a	13.08 \pm 1.87a	14.72 \pm 2.48a	43.14 \pm 4.39A
<i>Sorbaria sorbifolia</i>	114.22 \pm 2.52c	91.59 \pm 2.21b	43.59 \pm 4.14a	249.35 \pm 3.84AB

Notes: a, b, c in the same row indicate the significance different at $p < 0.05$. A, B, C in the same line indicates the significance different at $p < 0.05$.

Distribution of TN and TP in tissues

The accumulated quantities of TN in roots, stems and foliage accounted for 23–48%, 18–56% and 8–52%, respectively, of the total accumulations (Fig. 3). The proportions of TP in roots, stems, and foliage were 21–55%, 20–56% and 11–43%, respectively, of the total accumulations (Fig. 3).

Table 3: Spearman correlation coefficient of TN and TP accumulations in different tissues.

Tissues	Nutrient	Roots		Stem		Foliage	
		TN	TP	TN	TP	TN	TP
Roots	TN	1	0.92**	0.91**	0.89**	0.89**	0.88**
	TP		1	0.87**	0.90**	0.84**	0.84**
Stem	TN			1	0.95**	0.85**	0.81**
	TP				1	0.85**	0.84**
Foliage	TN					1	0.96**
	TP						1

Notes: ** Correlation is significant at the 0.01 level (2-tailed). TN is Total Nitrogen; TP is Total Phosphorus.

Based on the distribution of nutrient accumulations, the tested species were clustered into three distinct groups by Hierarchical cluster analysis (Fig. 4). The first group, including only two species, had a relatively higher proportion of nutrients (more than 50%) in stems; the second group included 9 species in which roots had the highest percentages of nutrients (about 45%). Foliage and stems shared almost the equal proportions. The third group, including 5 species, shared nearly equal percentages of nutrients in roots, stems and foliage. Species of the same families were clustered into the same groups (except *Quercus mongolica*).

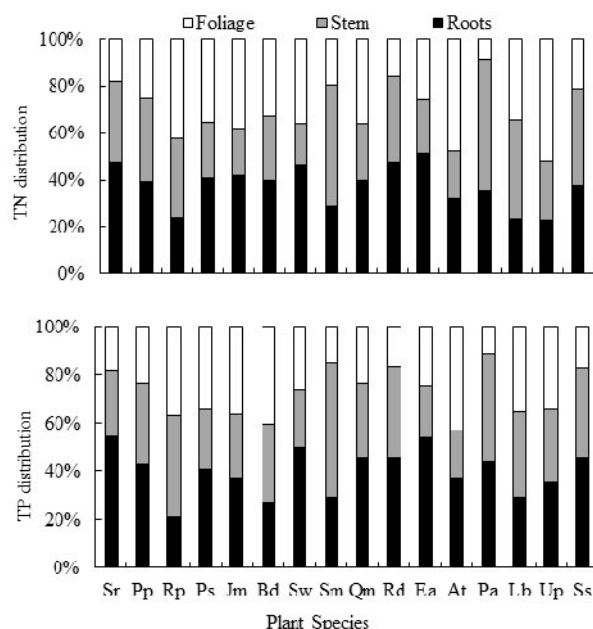


Fig. 3: Total nitrogen and total phosphorus distribution in roots, stem and foliage. *Syringa reticulata* (Sr), *Prunus padus* (Pp), *Robinia pseudoacacia* (Rp), *Pterocarya stenoptera* (Ps), *Juglans mandshurica* (Jm), *Berberis dielsiana* (Bd), *Sambucus williamsii* (Sm), *Salix matsudana* (Sm), *Quercus mongolica* (Qm), *Rosa davurica* (Rd), *Euonymus alatus* (Ea), *Acer truncatum* (At), *Populus alba* (Pa), *Lespedeza bicolor* (Lb), *Ulmus pumila* (Up) and *Sorbaria sorbifolia* (Ss).

Discussion

Interspecific variation

Biomass accumulations of nutrients varied by species (Fig. 1). These differences were largely determined by their physiology (i.e., net assimilation) and morphology (Ma et al. 2010), as many species have various mechanisms for adaptation, including ad-

justments of growth rate, modifications of plant structure (Li et al. 2007). Plants with high biomass accumulate more nutrients in their tissues (Jiang et al. 2011). *Robinia pseudoacacia* and *Lespedeza bicolor* yielded the highest biomass and accumulated the highest quantities of nutrients. Kyambadde et al. (2004) and Iamchaturapatr et al. (2007) report that species like *Robinia pseudoacacia* and *Lespedeza bicolor* are more suitable for riparian zone restoration owing to higher N and P removal from water.

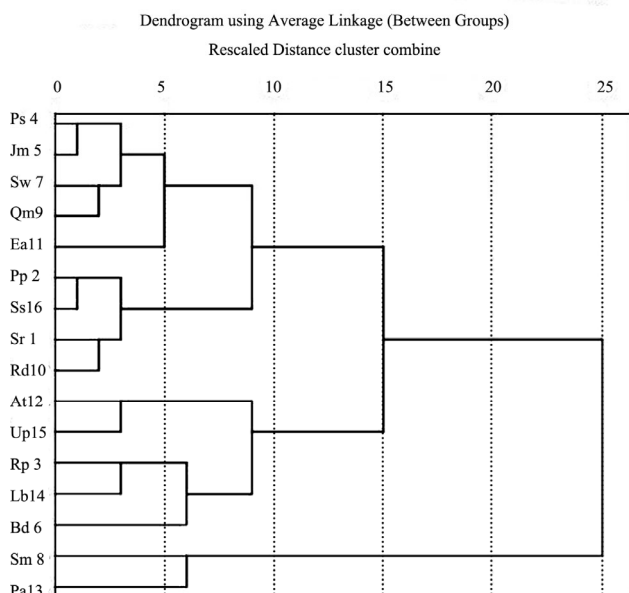


Fig. 4: Euclidean distance clustering tree. *Syringa reticulata* (Sr), *Prunus padus* (Pp), *Robinia pseudoacacia* (Rp), *Pterocarya stenoptera* (Ps), *Juglans mandshurica* (Jm), *Berberis dielsiana* (Bd), *Sambucus williamsii*, *Salix matsudana* (Sm), *Quercus mongolica* (Qm), *Rosa davurica* (Rd), *Euonymus alatus* (Ea), *Acer truncatum* (At), *Populus alba* (Pa), *Lespedeza bicolor* (Lb), *Ulmus pumila* (Up), and *Sorbaria sorbifolia* (Ss).

Boyd (1970, 1978) observed large interspecific variation in nutrient concentrations in aquatic plants. In his study, it is unclear whether such differences were related to environmental nutrient levels or to the different absorption rates of the various species because the plants were collected from the field. However, in our study, plants were of the same age and were cultivated in the same environment conditions. In the absence of other factors such as disturbance, interspecific variation in tissue TN and TP was recorded in our study. This result was in accordance with research on 41 wetland plants reported by McJannet (1995).

In our study, each species showed dramatically different TN and TP concentrations and accumulations between tissues (roots, stems and foliage). Nutrients were recorded at higher concentrations in foliage than in roots and stems. There were, however, no consistent differences in nutrient concentrations between roots and stems. This result was consistent with the results of Zhu et al. (2011). Li et al. (2013) reported nutrition distribution as foliage > stems > roots in 30 common plant species grown in the hydro-fluctuation belt of Baihua Reservoir in Guizhou prov-

ince, China. This was because both the structure and function differ by tissue type. Leaves contain photosynthetic tissues whose metabolism is active, while roots and stems are storage tissues that transport water and nutrients. Stems and roots, which were primarily composed of cellulose, have lower nutrition demand (Shan et al. 2011).

We recorded positive correlation between TN and TP. Niinemets and Kull (2003), however, found no correlation between TN and TP in plant species in a wooded meadow and a bog, probably because concentrations were similar in all species. In fact, both N and P can stimulate growth or other processes because TN supply affects how efficiently TP is acquired and used, and vice versa (Treseder and Vitousek 2001; Gusewell et al. 2003).

The function of riparian zone plants in nutrition removal

TN and TP concentration of the 16 woody plants ranged from 8.38 to 35.56 mg·g⁻¹ and from 0.87 to 5.49 mg·g⁻¹, respectively. TN and TP were accumulated to quantities ranging from 111.6 to 14729.73 mg and 16.06 to 1203.54 mg, respectively. Of the 16 woody plants, *Lespedeza bicolor*, *Robinia pseudoacacia*, and *Sorbaria sorbifolia* had absorbed most TN and TP from soil and stored most in tissues. These three species are recommended as preferred restoration plants for the main purpose of TN and TP removal in the riparian zone. Of course, the above results showed only the absorption and storage ability of the tested plant species. In other words, the data in Table 2 and Table 3 were just a part of the total removal effect by the whole riparian ecosystem. The riparian plant community provides a suitable environment for TN and TP removal (Wu et al. 2011). Other mechanisms, such as rhizosphere microbial activity and physical processes, could also contribute to the removal of most pollutants (Brix 1987; Gottschall et al. 2007). Consequently, the nutrient treatment and removal capacities of woody plants examined this study would, if grown in the wild, undoubtedly far exceed the results presented here. Due to the complexity of riparian ecosystems, more research is needed to learn more about the processes and mechanisms in natural situations.

Acknowledgement

We would like to thank Prof. Dali Tao, from Institute of Applied Ecology, Chinese Academy of Sciences, and Zhu Hong, the Editor of Journal of Forestry Research and Dr. Thomas D. Dahmer, the language editor of Journal of Forestry Research for their comments and suggestions on this manuscript.

References

- Bedford BL, Walbridge MR, Aldous A. 1999. Patterns in nutrient availability and plant diversity of temperate North American wetlands. *Ecology*, **80**(7): 2151–2169.
- Bennett EM, Carpenter SR, Caraco NF. 2001. Human impact on erodable phosphorus and eutrophication: A global perspective. *Bioscience*, **51**(3): 227–234.

- Borin M, Salvato M. 2012. Effects of five macrophytes on nitrogen remediation and mass balance in wetland mesocosms. *Ecol Eng*, **46**: 34–42.
- Boyd CE. 1970. Chemical Analyses of Some Vascular Aquatic Plants. *Archiv Fur Hydrobiologie*, **67**(1): 78–85.
- Boyd CE. 1978. *Chemical composition of wetland plants. Freshwater Wetlands: Ecological Processes and Management Potential*. New York: New York Academic Press, pp. 155–167.
- Brix H. 1987. Treatment of wastewater in the rhizosphere of wetland plants—the root-zone method. *Wat Sci Tech*, **19**(1/2): 107–118.
- Cooke JG. 1992. Phosphorus Removal Processes in a Wetland after a Decade of Receiving a Sewage Effluent. *Journal of environmental quality*, **21**(4): 733–739.
- Corwin DL, Vaughan PJ, Loague K. 1997. Monitoring nonpoint source pollutants in the vadose zone with GIS. *Environ Sci Technol*, **31**(8): 2157–2175.
- Dabrowski JM, Peall SKC, Van Niekerk A, Reinecke AJ, Day JA, Schulz R. 2002. Predicting runoff-induced pesticide input in agricultural sub-catchment surface waters: linking catchment variables and contamination. *Water Research*, **36**(20): 4975–4984.
- Giese LAB, Aust WM, Kolka RK, Trettin CC. 2003. Biomass and carbon pools of disturbed riparian forests. *Forest Ecol Manag*, **180**(1–3): 493–508.
- Gottschall N, Boutin C, Crolla A, Kinsley C, Champagne P. 2007. The role of plants in the removal of nutrients at a constructed wetland treating agricultural (dairy) wastewater, Ontario, Canada. *Ecol Eng*, **29**(2): 154–163.
- Gusewell S, Bollens U, Ryser P, Klotzli F. 2003. Contrasting effects of nitrogen, phosphorus and water regime on first- and second-year growth of 16 wetland plant species. *Functional Ecology*, **17**(6): 754–765.
- Haycock NE, Pinay G. 1993. Groundwater Nitrate Dynamics in Grass and Poplar Vegetated Riparian Buffer Strips during the Winter. *Journal of environmental quality*, **22**(2): 273–278.
- Hazlett P, Broad K, Gordon A, Sibley P, Buttle J, Larmer D. 2008. The importance of catchment slope to soil water N and C concentrations in riparian zones: implications for riparian buffer width. *Can J Forest Res*, **38**(1): 16–30.
- Hefting MM, Clement JC, Bienkowski P, Dowrick D, Guenat C, Butturini A, Topa S, Pinay G, Verhoeven JTA. 2005. The role of vegetation and litter in the nitrogen dynamics of riparian buffer zones in Europe. *Ecol Eng*, **24**(5): 465–482.
- Iamchaturapatr J, Yi SW, Rhee JS. 2007. Nutrient removals by 21 aquatic plants for vertical free surface-flow (VFS) constructed wetland. *Ecol Eng*, **29**(3): 287–293.
- Jiang FY, Chen X, Luo AC. 2011. A comparative study on the growth and nitrogen and phosphorus uptake characteristics of 15 wetland species. *Chem Ecol*, **27**(3): 263–272.
- Kuusemets V, Mander U, Lohmus K, Ivask M. 2001. Nitrogen and phosphorus variation in shallow groundwater and assimilation in plants in complex riparian buffer zones. *Water Sci Technol*, **44**(11–12): 615–622.
- Kyambadde J, Kansime F, Gumaelius L, Dalhammar G. 2004. A comparative study of *Cyperus papyrus* and *Miscanthidium violaceum*-based constructed wetlands for wastewater treatment in a tropical climate. *Water Research*, **38**(2): 475–485.
- Lee CG, Fletcher TD, Sun GZ. 2009. Nitrogen removal in constructed wetland systems. *Eng Life Sci*, **9**(1): 11–22.
- Li M, Wu YJ, Yu ZL, Sheng GP, Yu HQ. 2007. Nitrogen removal from eutrophic water by floating-bed-grown water spinach (*Ipomoea aquatica* Forsk.) with ion implantation. *Water Research*, **41**(14): 3152–3158.
- Li XF, Li QH, Qin HL, Chen FF, Liu SP, Gao TJ, Ou T. 2013. Distribution characteristics of N, P and K contents in 30 common plants from the hydro-fluctuation belt of Baihua Reservoir. *Acta Scientiae Circumstantiae*, **33**(4): 1089–1097. (In Chinese)
- Lowrance R, Altier LS, Newbold JD, Schnabel RR, Groffman PM, Denver JM, Correll DL, Gilliam JW, Robinson JL, Brinsfield RB, Staver KW, Lucas W, Todd AH. 1997. Water quality functions of Riparian forest buffers in Chesapeake Bay watersheds. *Environ Manage*, **21**(5): 687–712.
- Lowrance R, Todd R, Fail J, Hendrickson O, Leonard R, Asmussen L. 1984. Riparian Forests as Nutrient Filters in Agricultural Watersheds. *Bioscience*, **34**(6): 374–377.
- Lu R. 1999. *Soil agrochemical analysis*. Beijing: China Agricultural Science and Technology Press, p. 296–300. (In Chinese)
- Ma PL, Pu JY, Zhao CY, Wang WT. 2010. Influence of light and temperature factors on biomass accumulation of winter wheat in field. *The Journal of Applied Ecology*, **21**(5): 1270–1276. (In Chinese)
- McBroom MW, Beasley RS, Chang M, Ice GG. 2008. Water quality effects of clearcut harvesting and forest fertilization with best management practices. *Journal of Environmental Quality*, **37**(1): 114–124.
- McClain ME, Boyer EW, Dent CL, Gergel SE, Grimm NB, Groffman PM, Hart SC, Harvey JW, Johnston CA, Mayorga E, McDowell WH, Pinay G. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. *Ecosystems*, **6**(4): 301–312.
- Mcjannet CL, Keddy PA, Pick FR. 1995. Nitrogen and Phosphorus Tissue Concentrations in 41 Wetland Plants - a Comparison across Habitats and Functional-Groups. *Functional Ecology*, **9**(2): 231–238.
- Niinemets U, Kull K. 2003. Leaf structure vs. nutrient relationships vary with soil conditions in temperate shrubs and trees. *Acta Oecologica-International Journal of Ecology*, **24**(4): 209–219.
- Osborne LL, Kovacic DA. 1993. Riparian Vegetated Buffer Strips in Water-Quality Restoration and Stream Management. *Freshwater Biol*, **29**(2): 243–258.
- Shan BQ, Ao L, Hu CM, Song JY. 2011. Effectiveness of vegetation on phosphorus removal from reclaimed water by a subsurface flow wetland in a coastal area. *J Environ Sci-China*, **23**(10): 1594–1599.
- Son Y, Gower ST. 1992. Nitrogen and phosphorus distribution for five plantation species in southwestern Wisconsin. *Forest Ecol Manag*, **53**(1–4): 175–193.
- Spoelstra J, Schiff SL, Semkin RG, Jeffries DS, Elgood RJ. 2010. Nitrate attenuation in a small temperate wetland following forest harvest. *Forest Ecol Manag*, **259**(12): 2333–2341.
- Tanner CC. 1996. Plants for constructed wetland treatment systems - A comparison of the growth and nutrient uptake of eight emergent species. *Ecol Eng*, **7**(1): 59–83.
- Treseder KK, Vitousek PM. 2001. Effects of soil nutrient availability on investment in acquisition of N and P in Hawaiian rain forests. *Ecology*, **82**(4): 946–954.
- Wu HM, Zhang JA, Li PZ, Zhang JY, Xie HJ, Zhang B. 2011. Nutrient removal in constructed microcosm wetlands for treating polluted river water in northern China. *Ecol Eng*, **37**(4): 560–568.
- Yu S, Chen W, He X, Liu Z, Song H, Ye Y, Huang Y, Jia L. 2014. A comparative study on nitrogen and phosphorus concentration characteristics of twelve riparian zone species from upstream of Hunhe River. *CLEAN-Soil, Air, Water*, **42** (4): 408–414.
- Zhu LD, Li ZH, Ketola T. 2011. Biomass accumulations and nutrient uptake of plants cultivated on artificial floating beds in China's rural area. *Ecol Eng*, **37**(10): 1460–1466.